SEARCH FOR X-RAY CHANNELING RADIATION AT FERMILAB’S FAST FACILITY

by

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DEPARTMENT APPROVAL

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This thesis has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

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The Fermilab FAST facility has capability of producing a 50 GeV electron beam, which will be used to generate hard x-rays through a process called Channeling Radiation. This paper will investigate experimental solutions for high background during the beginning of the Channeling Radiation study, as well as propose ideas for modifying the beam line to decrease background.
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## Contents

Table of Contents vi

List of Figures vii

1 Introduction 1

2 Background 4
  2.1 Background of Channeling Radiation 4
  2.2 Classical Description of Channeling Radiation 5
  2.3 Equations of Motion 7
  2.4 Quantum Description of Channeling Radiation 8
  2.5 Multiple Scattering 9

3 Experimental Setup 10

4 Experimental Problem-Solving 12
  4.1 Bremsstrahlung 12
  4.2 Dark Current 15
  4.3 Crystal Alignment 17
  4.4 Detector Saturation 19
  4.5 Attenuation 21

5 Future Work and Conclusion 23
  5.1 Future Work 23
  5.2 Conclusion 24

Bibliography 25

A Bremsstrahlung Analysis Code 26

B Heat Map Code 31

C Attenuation Code 33

Index 39
## List of Figures

1.1 Schematic diagram of the electron beam oscillating in the field of crystal atoms [4] ................................................................. 2

2.1 Ion trajectories in the material during channeling radiation are like balls on a string. [1] .......................................................... 5

2.2 The motion and potential of the lab frame and the rest frame of the experiment. [1] ................................................................. 8

3.1 Layout of the experiment [2] ................................................................. 10

3.2 Close up schematic diagram of the end of the experiment, including the Crystal positioning apparatus. [2] ................................. 11

4.1 GEANT4 simulations of BS spectra of the 4 most common FAST beamline materials: 2 mm stainless steel (top left), 5 mm Cu frame (top right), 0.5 mm Al foil (low left) and 3 mm Nb (low right). [3] .......................... 13

4.2 Comparisons of theoretical spectra generated by GEANT 4 of Al and Steel with the experimental spectra. By comparing theoretical and experimental spectra, one can tell that the main source of BS in this case is from Aluminium. ................................................................. 14

4.3 As the beam goes through the chicane, highlighted in orange, some of the electrons continue to be bent straight toward the 90-degree detector. [2] ................................................................. 14

4.4 An x-ray spectra is detected. However, the beam line is turned off and this spectra is created entirely of dark current. ..................... 16

4.5 The gun dark current was reduced significantly by reducing the gun exit energy to 3.5 MeV (left). Even with the lower gun gradient, dark current from the gun dominated the overall bunch signal, as shown (right) for a 200 fC/pulse signal. [4] ............................................. 17

4.6 Steel bremsstrahlung overwhelms any potential CR signal. .......... 18

4.7 No one region of pitch and yaws were favored over another. More runs of this program are needed to find the ideal pitch and yaw. ....... 19

4.8 Beam charge and photon count should be linearly related. This graph illustrates that that is not the case. ....................... 20
4.9 When bunch charge was lowered significantly and the 90 degree detector was used in addition, data that looked like what was predicted came about. .................................................. 21
4.10 Attenuation affects low-energy photons, but not the majority of the photons. .................................................. 22
Chapter 1

Introduction

Channeling radiation is the coherent scattering of electrons, the steering of their motion through single crystals along crystallographic strings or planes, which emits electromagnetic radiation. Channeling Radiation (CR) is generated by charged beams (typically electrons or positrons) passing through a crystal parallel with a crystallographic plane [2]. Electrons may oscillate perpendicular to the plane and generate CR which propagates in the same direction as the incident beam [1]. Electron beams with moderate energy ranging from 4 to 50 MeV can be used to produce x-rays through Channeling Radiation. The x-ray spectrum from electron beams extends up to 140 keV, and this range covers the demand for most practical applications [5]. The beam experiment at the Fermilab Accelerator Science and Technology (FAST) facility has a beam energy of 50 MeV, and offers the possibility of a precise, tunable x-ray source. This paper will give a brief overview of FAST’s channeling radiation experiment, and the progress made in achieving x-ray channeling radiation.

The channeling effect of electrons was discovered by computer simulations of the motion of ions in crystals in the early 1960s. In order to achieve channeling radiation, an electron beam enters a single, highly symmetric crystal. The electron beam
oscillates in the field of the crystal’s atoms. While traveling through the crystal, the electrons in the beam "oscillate" from one bound state to another, emitting electromagnetic radiation in the form of x-rays. Figure 1.1 is a schematic diagram that illustrates the concept of Channeling Radiation.

![Figure 1.1 Schematic diagram of the electron beam oscillating in the field of crystal atoms [4]](image)

Although the oscillation frequency is rather low and corresponds to the radiation energy, relativistic effects such as the Lorentz contraction of the longitudinal coordinate and the Doppler effect transform the energy of emitted CR photons observed in the direction of the beam into the domain of x-rays. The electron perceives the common action of the individual atomic potentials of the plane as such of a continuous one. This means that the crystal plane is assumed to be charged continuously, forming an average one dimensional transverse continuum potential.

There is an interest in channeling radiation because it is more intense than bremsstrahlung, and more monochromatic than synchrotron radiation. It is directed into a narrow forward cone and energetically shifted into the domain of x- or γ-rays. The intense x-rays can be used in material physics, biophysics, and medical applications. For example:

- X-ray photoelectron spectroscopy - chemical analysis technique used in surface physics
- Medical Applications - sharp visualizations of coronary arteries and detection
of tumors

- X-ray crystallography - using x-rays to determine the structure of proteins or other materials

This experiment will be a smaller, less expensive method of generating intense x-rays compared to synchrotron radiation.
Chapter 2

Background

2.1 Background of Channeling Radiation

Channeling radiation is the oscillation motion of charged particles that lead to radiation emission. When this concept was first thought about during the 1960s, it was not a new concept. [1] Bremsstrahlung had been known for nearly a hundred years. Scientists theorized that charged particles moving transversely through a medium could lead to a emission of radiation, but theoretically because the emission frequencies $\omega_0$ were so low, the corresponding energies $\hbar\omega_0$ would be only in the range of a few eV. Then, along came quantum mechanics and relatively effects. Kumakhov et al. [1] was one of the first groups to realize that relativistic effects would shift the resulting photon energy to the keV to MeV range. After this realization, physicists became more interested in investigating this alternative way of producing radiation.

Experimental channelling was discovered by Lindhard in 1965, after measuring and calculating ion ranges in crystals. In a classical sense, those ion trajectories are governed by correlated soft collisions. The following section will provide a classical description of Channeling Radiation, while the next section will provide a brief
Quantum Mechanical explanation of Channeling Radiation (CR).

2.2 Classical Description of Channeling Radiation

Channeling Radiation is due to soft collisions of electrons (or positrons) with atoms in a material, the material is assumed to be crystalline. CR results from constructive interferences of the electromagnetic radiation of those collisions. The figure below illustrates the classical description of channeling radiation

![Figure 2.1](image-url)

Figure 2.1 Ion trajectories in the material during channeling radiation are like balls on a string. [1]

The Jolson angles, also known as deflection angles, are quite small. The momentum transfer of the deflection of the atoms can be approximated from a single collision because of the small deflection angle. The following equation is the change of momentum of the ions:

\[
\delta p \simeq \frac{1}{\nu} \int_{-\infty}^{+\infty} dz \nabla_r V_a(r, z)
\]  

(2.1)

where the direction of motion is almost always in the z direction. \(V_a(r, z)\) is the potential of the ions in the r and z direction. The transverse motion of the channeled electrons is restricted to discrete channeling states of the continuum potential. The equation for motion is governed by a continuum planar potential, as described in Equation 2.2 below.
2.2 Classical Description of Channeling Radiation

\[ V(x) = N d_p \int_{-\infty}^{+\infty} dy dz V_a(x, y, z) \]  \hspace{1cm} (2.2)

where \( x \) is the coordinate perpendicular to the planes, \( N \) is the atomic density of the crystal, \( d_p \) is the spacing of the planes and therefore \( N d_p \) is the density of atoms in the plane.

In a continuum approximation there is a difference between longitudinal motion and transverse motion. Transverse motion is modeled by an effective Hamiltonian, which in the axial case is given by:

\[ H_\perp(r, p) = \frac{p^2}{2M_1} + U_T(r) \]  \hspace{1cm} (2.3)

where \( M_1 \) is the projectile mass, which is relativistic and \( U_T(r) \) is the potential energy of the electrons in the beam. The transverse kinetic energy can be written as

\[ E^{\text{kin}}_\perp = \frac{1}{2} p^2 \psi^2 + U_T(r) \]  \hspace{1cm} (2.4)

Penetration to the center of the crystal is forbidden if this energy is lower than the continuum potential shown in Equation 2.2. This condition leads to the existence of a critical angle. If the electrons hit a crystal (or other material) at an angle greater than the critical angle, channeling radiation cannot occur. The critical angle is approximately equal to the following equation in the case of a one projectile and one atom:

\[ \psi_1 = \left( \frac{2Z_1 Z_2 e^2}{1/2 pvd} \right)^{1/2} \]  \hspace{1cm} (2.5)

The critical angle for an electron on a plane, such as a crystal is:

\[ \psi_p = \left( \frac{2Z_1 Z_2 e^2}{1/2 pvd} \right)^{1/2} \left( \frac{Ca}{d} \right)^{1/2} \]  \hspace{1cm} (2.6)
2.3 Equations of Motion

One of the main reasons channeling radiation even works is due to the effects of relativity on the electron beam and the atoms in the material it is colliding with. The equations of motion of channeling radiation all incorporate a relativistic factor $\gamma$. The transverse motion of CR is generated by the continuum potential in the following equation:

$$\gamma(t)m\ddot{x}(t) = -[1 - (\dot{x}/c^2)]dV/dx \quad (2.7)$$

Because the quantity $\dot{x}/c^2$ is ultimately neglected, this equation reduces to:

$$\frac{1}{2}\gamma m(\dot{x})^2 + V[x(t)] = E_{\perp} \quad (2.8)$$

The time dependence on $gamma$ is not always important, but it is responsible for the deviation of the longitudinal motion from a uniform translational motion.

The following diagram illustrates the motion and potential of the electron in the material.

Another form of motion in channeling radiation is the characteristic frequency. It corresponds to the periodic crossing of planes by the electron. The associated radiation from this frequency is coherent Bremsstrahlung. For a channeling positron moving in the $z$ direction with average velocity $c < \beta_z >$ and an oscillation frequency of $\omega_0(E_\perp)$, the limit of oscillation during a time $T$ spent in the crystal is:

$$\omega(1 - \cos \Theta < \beta_z >) = n\omega_0(E_\perp), n = 1, 2, 3... \quad (2.9)$$
In the average rest frame, the system can only radiate with frequencies that are integral multiples of the characteristic orbital frequency. There is also a longitudinal oscillation caused by the magnetic field, with an amplitude smaller than that of transverse oscillation. In Figure 2.2, it illustrates this difference between the lab frame and the rest frame.

2.4 Quantum Description of Channeling Radiation

Due to the complexities of the quantum mechanical description of channeling radiation, a conceptual description will only be written. Detailed equations will be omitted. Planar interaction potential of channeling radiation is one-dimensional. The transverse motion of the electron can be described by a Schrödinger equation:

\[
\left[ \frac{\hbar^2}{2m\gamma} x^2 + V(x) \right] u(x) = E_x u(x) \tag{2.10}
\]

where \(E_x\) is the transverse energy and \(u(x)\) is the wave function of the electron. It could also be modeled by a Fourier series because of the periodic nature of the planar
2.5 Multiple Scattering

potential:

\[ V(x) = \sum_n v_n e^{inx} \quad n = \ldots, -1, 0, 1, 2 \ldots \]  

(2.11)

In channeling radiation, the electron (or positron) follows a path that brings it into periodic contact with the crystal’s atoms. In a more quantum picture, the radiation frequency described in equation 2.9 is actually determined by energy-momentum balance.

2.5 Multiple Scattering

Sometimes, the channeling radiation in the crystal can be scattered in multiple directions. Multiple scattering leads to line broadening. In addition, scattering parallel to the plane reduces the sharpness of the cut-off. This is due to a limitation of the coherence length for emission, and leads to a small reduction of the cut-off frequency. Multiple scattering also results in a peak-energy shift downwards to a smaller energy and an asymmetric CR line shape. This line shape could be successfully simulated by the convolution of the intrinsic Lorentizian line shape with a Gaussian-like distribution to account for electron multiple scattering during channeling radiation. [5] Due to all of these effects, crystal alignment during the experiment is crucial.
Chapter 3

Experimental Setup

A schematic layout of the SRF-based photoinjector, which is the low energy section of Fermilab’s Channeling Radiation experiment, can be found in Fig. 3.1.

![Layout of the experiment](image)

**Figure 3.1 Layout of the experiment [2]**

The photoinjector consists of an RF gun, the two accelerating cavities CAV1, CAV2, the two sets of quadrupole triplets separated by a bunch compressor (BC1), the goniometer (containing the crystal), the vertical dipole magnet for transporting the electrons to the dump and the forward x-ray detector [6]. The crystal used for FAST’s experiment is diamond. Diamond crystals have been discovered to be
probably the most suitable ones for the production of intense CR because of their outstanding parameters such as low atomic number, nearly perfect structure, high Debye temperature, and large thermal conductivity. Another view of the experimental setup, including details of the crystal position and the 90-degree detector is illustrated below.

Figure 3.2 Close up schematic diagram of the end of the experiment, including the Crystal positioning apparatus. [2]

There are dipole correctors and diagnostic devices including beam current and beam loss monitors and Yag screens for measuring the electron beam size. The electron beam has an energy of 5 MeV after the rf gun while the cavities CC1 and CC2 are expected to increase the beam energy roughly by 23 MeV and 16 MeV respectively. The beam energy as it enters the crystal is 43 MeV.
Chapter 4

Experimental Problem-Solving

4.1 Bremsstrahlung

Bremsstrahlung radiation is produced by the acceleration or especially the deceleration of a charged particle after passing through the electric and magnetic fields of a many atoms. Similar to channeling radiation, the charged particle falls from a free state to a bound state. Experimental spectra can be compared to known bremsstrahlung spectrum caused by one material. These bremsstrahlung spectra were generated using a simulation program called GEANT4. Before the experiment occurred, it was predicted that the largest source of background to the channeling radiation was to be bremsstrahlung (BS) from the crystal or other sources. A copy of those Bremsstrahlung spectra generated by GEANT4 is shown below in Figure 4.1. In addition, a copy of one of the five codes used to generate these spectra are in Appendix A.

By comparing the spectrum of the experiment to these known spectra, it could be used to determine what is causing background to the channeling radiation, as illustrated by Figure 4.2. In this particular case, it appears as though aluminium is...
4.1 Bremsstrahlung

Figure 4.1 GEANT4 simulations of BS spectra of the 4 most common FAST beamline materials: 2 mm stainless steel (top left), 5 mm Cu frame (top right), 0.5 mm Al foil (low left) and 3 mm Nb (low right). [3]

the main source of BS during that particular run of the experiment. After making this discovery, the experimental set up is to be reviewed to find where aluminium is found. In the experiment, the beam line itself is made of aluminium- meaning that, it is very likely that the electron beam is somehow hitting the beam line itself. Calibrations and adjustments are made in order to correct the alignment and decrease or eliminate the bremsstrahlung background noise.

It could be concluded that the background is coming from an aluminum source, and not a steel source. These bremsstrahlung background source studies were continued throughout the experiment, as there were many causes of bremsstrahlung background.

Another possible source of the aluminium bremsstrahlung is not due to improper
4.1 Bremsstrahlung

Figure 4.2 Comparisons of theoretical spectra generated by GEANT 4 of Al and Steel with the experimental spectra. By comparing theoretical and experimental spectra, one can tell that the main source of BS in this case is from Aluminium.

alignment of the beam line, but the electron beam not being fully bent around a piece of the experiment called the chicane. The chicane is a series of magnets that bend the electron beam in order to reduce dark current. Figure 4.3 highlights where the chicane is located. During the experiment, the forward detector became saturated (this will be discussed in further detail in section 4.3), causing the 90-degree detector to be used exclusively instead.

Figure 4.3 As the beam goes through the chicane, highlighted in orange, some of the electrons continue to be bent straight toward the 90-degree detector. [2]

Therefore, it is difficult to determine whether the bremsstrahlung is due to misalignment of the electron beam in the beam line or from the chicane not properly bending the electron beam. In the future, lead shielding will be placed in strategic locations.
4.2 Dark Current

In physics and in electronic engineering, dark current is the relatively small electric current that flows through photosensitive devices such as a photomultiplier tube, photodiode, or charge-coupled device even when no photons are entering the device. It consists of the charges generated in the detector when no outside radiation is entering the detector. Physically, dark current is due to the random generation of electrons within the depletion region of the device.

Before the Channeling Radiation at FAST was created, it was stated that, “Dark current from the rf gun may also create some background, but it is likely that this dark current will be bent away from the crystal by the bunch compressor chicane upstream of the crystal.” [2] This is why the chicane, highlighted in orange in Fig. 4.3 is used in the first place. One solution to the dark current problem was also the cause of bremsstrahlung background noise.

During test runs it was discovered that RF gun creates the dark current, not the cavities - meaning that even when the beam is off, x-rays are detected. Because the RF gun creates the initial electron beam of 5 MeV, the electrons can tunnel through a surface barrier modified by the presence of an electric field, resulting in a field emission current. Figure 4.4 illustrates that even when the beam is off, the RF gun creates dark current that is detected at the end of the beam line.

To try to first solve the problem, the cavity gradient was lowered and the RF pulse was shortened. Essentially, the RF gun’s power was lowered. This was done to more closely match the number of pulses in the pulse train provided by the drive laser within the macropulse [4] (see Fig. 4.5). Reducing the gradient, and consequently the
4.2 Dark Current

An x-ray spectra is detected. However, the beam line is turned off and this spectra is created entirely of dark current.

RF-gun field, however also reduces the overall beam energy resulting in a trade-off with space-charge effects and greater overall focusing through the superconducting radiofrequency (SRF) structures in the graphs below.

Between the electron gun and the first SRF cavity, a collimator can be inserted. The collimator was intended to be used in conjunction with a dark current kicker to provide longitudinal scraping of dark current as well, but the kicker has not been installed. This limits the reduction in dark current only to the transverse collimator aperture [3]. The gun cavity solenoids were adjusted to optimally scrape remaining dark current.

Throughout the crystal collimation effort, the beam was accelerated through the two SRF booster cavities that follow the gun to about 43 MeV. Because the beam itself was accelerated on-crest through the CC1 magnet (maximum energy gain), it follows that any dark current remaining will have lower energy. The chicane being a dispersive segment of the low energy beamline, allowed selective scraping of the lower energy dark current.

The amount scraped away with the crystal collimation was not well regulated.
4.3 Crystal Alignment

One of the most vital conditions to enable Channeling Radiation is the crystal position. The Miller indices for the diamond crystal planes is set at (110). However, the pitch and yaw of the crystal still needs to be determined. At the time of this paper, only a small region was studied. No particular pitch or yaw orientation seemed to produce more channeling radiation than another.

As evidenced by Fig 4.6, steel bremsstrahlung appears to overwhelm the x-ray signal. Any channeling radiation that could be generated would be covered by steel
4.3 Crystal Alignment

Steel bremsstrahlung overwhelms any potential CR signal. It is believed that bremsstrahlung is being created from scraping the beam in the chicane in an attempt to remove dark current.

A program was created to automatically and precisely adjust the pitch and the yaw of the crystal and do a single run of channeling radiation experiment over the course of several days. The amount of photon counts were recorded in hopes of finding a perfect position of the crystal. A heat map was created to model the ratio of the highest peaks to the average value of the graph. The code that created this graph is posted in Appendix B.

One would expect the heat map to have a certain region of pitches and yaws that are quite similar to have similar ratios. This was not the case. If one looks at the heat map, they can also observe the fact that the ratios of the peaks to the mean of the graph are quite small. The heat map illustrates that in the limited run of the pitch and yaw program, the ideal pitch and yaw was not located. More runs of this program could not be completed at the time due to Fermilab’s beam being shut down for annual maintance.
According to equation 4.1, the rate of photons detected should increase linearly with bunch charge. However, the forward detector was becoming saturated, and did not count all photons. When bunch charge was reduced from 20 pC to 0.05 pC, most photons emitted were detected.

\[
Rate_{\text{photons detected}} = \frac{\text{Bunch Charge}}{\text{Charge of an Electron}} \times \frac{\text{Area} \times \gamma}{4R^2} \times \frac{\text{Bunches}}{\text{Macropulse}} \times \frac{\text{Macropulses}}{\text{Second}}
\]  

(4.1)

It scales more linearly with the bunch charge on the 90 detector, this allowed for higher bunch charges without saturation.

In order to decrease detector saturation, a detector which is offset by 90 is utilized. After the beam line passes through the diamond crystal, a plastic plate could be inserted in the beam line. The x-rays would then be Compton scattered off of the plate to the 90 detector. It should be noted that through Compton scattering, the photon
4.4 Detector Saturation

![Graph of Bunch Charge vs Recorded (Slow) Photon Counts]

**Figure 4.8** Beam charge and photon count should be linearly related. This graph illustrates that that is not the case.

energy decreases. However, simulations have shown that the energy decrease of the photons should not be more than 10% of the original photon energy. Only a small percentage of the x-rays are Compton scattered to the 90° detector, which eliminates detector saturation. By using the 90° detector, bunch charge can be increased to 20 pC. Figure 4.7 and 4.8 on the following page illustrates how bunch charge was not increasing photon count, and the results of lowering the bunch charge and switching to the 90° detector.
Figure 4.9 When bunch charge was lowered significantly and the 90 degree detector was used in addition, data that looked like what was predicted came about.

4.5 Attenuation

The signal of the x-ray photons is reduced through attenuation as it travels through air. It was important to investigate the full extent of attenuation, and see how much it truly affects the photon count. Attenuation is calculated using the following equation:

\[
\frac{I_T(E)}{I_0(E)} = \exp\left(-\frac{L}{L_{abs}}\right)
\]  \hspace{1cm} (4.2)

Where \(I_0(E)\) is the incident beam on the material, in this particular experiment a diamond crystal, \(I_T(E)\) is the transmitted intensity, and \(L\) is the length that the photons travel before they reach the detector (3 meters). \(L_{abs}\) is represented by equation 4.3

\[
L_{abs} = \frac{1}{\mu \rho}
\]  \hspace{1cm} (4.3)

\(\mu\) is an attenuation coefficient dependent upon \(L\), which is interpolated from a data file of \(\mu\) at shorter distances than \(L\). The program code of the interpolation and
4.5 Attenuation

Figure 4.10 Attenuation affects low-energy photons, but not the majority of the photons.

attenuation calculation can be found in Appendix C. $\rho$ is simply the density of the material the photons travel through, or in this case the density of air in $g/cm^2$.

Attenuation was incorporated into theoretical models using the above equations. The graph below illustrates how attenuation affects x-ray photon spectra. In Figure 4.10, the red are a model of theoretical photon counts before attenuation, and the green line represents the theoretical model with attenuation incorporated. Attenuation appears to significantly affect photons at low energies, but for the rest of the x-ray energy spectra, attenuation does not seem to affect them.
Chapter 5

Future Work and Conclusion

5.1 Future Work

There are several things that can be modified in the second run of FAST’s channeling radiation experiment. In the future, it is proposed that more shielding be added around the detector to block off dark current and other background. It is believed that radiation from the chicane is hitting the 90-degree detector, and studies need to be conducted to prove if this belief is true. If this is the case, the researches will need to assess if the chicane is needed to reduce dark current. In addition, moving the 90-degree detector to the other side of the beam line would greatly reduce background.
5.2 Conclusion

Channeling Radiation has the ability to produce high-intensity x-rays, and Fermilabs FAST facility will have the capability to produce Channeling Radiation. There were problems with dark current and detector saturation, but solutions have been proposed. Channeling radiation is within reach at FAST, and will allow for more research capabilities in many fields.
Bibliography


Appendix A

Bremsstrahlung Analysis Code

import numpy as np
from io import StringIO
import math
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit

#load up the file you want the rms of
x1, y1 = np.loadtxt('DATA_VU_20160628_143626',usecols=(0,1), unpack=True)

#calculate the square of all the y-values
ysq = (y1)**2

#find the number of values in the y1 array
n = len(y1)

#sum up all the values in ysq

ysum = np.sum(ysq)

# put it all together
rms = math.sqrt(ysum/n)
print 'rms = ',rms

#give values for every number above the rms value
i = 0
yrms = np.zeros(n)

print "Energy values above 2.3 sigma:"

while (i < n):
if y1[i] > 2.3*rms:
en = (x1[i]/1024)*150
print en
i+=1
else:
i+=1

# find where the largest value is
j = 0
ybig = 0
b = 0

while (j < n):
if y1[j] > 0 and y1[j] > ybig:
ybig = y1[j]
b = j
j+=1
else:
j+=1

print 'The largest energy value is', (x1[b]/1024)*150
energy = (150*x1)/1024

np.savetxt('energy1.txt', np.c_[energy,y1])

# Subtract values from the bremsstrahlung equation

xdata, ydata = np.loadtxt('bremdata1.txt',usecols=(0,1), unpack=True)

def func(xdata, a, b):
    return (a)/(xdata)+b

popt, pcov = curve_fit(func, xdata, ydata,p0=[200,2])
a1 = popt[0]
b1 = popt[1]
popt[1] = popt[1]-13
popt[0] = popt[0]+1000

print "The function is best modeled by:\",a1,"/\",x","+,b1
xx = x1
yy = func(xx, *popt)

#Subtract the two functions
ynew = abs(y1-yy)

# See if there are any values above 3 sigma in the difference curve.
ysq2 = (ynew)**2
ysum2 = np.sum(ysq2)
rms2 = math.sqrt(ysum2/n)

print "Energy values above 3 sigma in the difference function:"
i=0

#j is the x-value of whatever number is above 3 sigma
while (i < n):
    if ynew[i] > 3*rms2:
        en = (x1[i]/1024)*150
        print en
        i+=1
    else:
        i+=1

np.savetxt('diff.txt', np.c_[x1,ynew])

x1 = (x1/1024)*150
# Plot three functions. Today's data, bremsstrahlung, and then the subtracted function.

```python
plt.figure()
plt.plot(x1, yy, 'm-', lw=3, label="Bremsstrahlung Best-Fit Curve")
plt.plot(x1, y1, 'b-', label="Today's Data")
plt.plot(x1, ynew, 'r-', label="Difference Curve")
plt.title('Theoretical Bremsstrahlung')
plt.ylabel('Photon Counts')
plt.xlabel('X-ray Energy (in keV)')
plt.legend()
plt.show()
```
Appendix B

Heat Map Code

```python
import matplotlib.pyplot as plt
import numpy as np

# here's our data to plot, all normal Python lists
x = [47.54, 47.58, 47.62, 47.66, 47.70, 47.74, 47.78, 47.82]
y = [70.31, 70.37, 70.43, 70.49, 70.55]

# The intensity was calculated by dividing the
# highest peak of photon counts with the average
# value of the photon counts.
```

Most heatmap tutorials I found online use `pyplot.pcolormesh` with random sets of data from Numpy; I just needed to plot x, y, z values stored in lists--without all the Numpy mumbo jumbo. Here I have code to plot intensity on a 2D array, and I only use Numpy where I need to (pcolormesh expects Numpy arrays as inputs).

```python
import matplotlib.pyplot as plt
import numpy as np

# here's our data to plot, all normal Python lists
x = [47.54, 47.58, 47.62, 47.66, 47.70, 47.74, 47.78, 47.82]
y = [70.31, 70.37, 70.43, 70.49, 70.55]

# The intensity was calculated by dividing the
# highest peak of photon counts with the average
# value of the photon counts.
```
intensity = [
    [0.8838, 0.8, 1.0818, 0.8602, 0.8400, 0.9010, 1.0619, 1],
    [0.8152, 0.8444, 0.9669, 0.9508, 0.8349, 0.8720, 0.8, 1],
    [0.8, 0.8, 1.0857, 0.8640, 0.9079, 0.9056, 0.8, 1],
    [0.8190, 0.9424, 0.9216, 0.8367, 1.0163, 0.8917, 0.8, 1],
    [0.8190, 0.9424, 0.9216, 0.8367, 1.0163, 0.8917, 0.8, 1]
]

#setup the 2D grid with Numpy
x, y = np.meshgrid(x, y)

#convert intensity (list of lists) to a numpy array for plotting
intensity = np.array(intensity)

#now just plug the data into pcolormesh, it’s that easy!
plt.pcolormesh(x, y, intensity)
plt.colorbar() #need a colorbar to show the intensity scale
plt.show() #boom
Appendix C

Attenuation Code

```python
import numpy as np
from io import StringIO
import math
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit

# Import attenuation constants from file
x1, y1 = np.loadtxt('AttenCoeff_Air.txt', usecols=(0,1), unpack=True)

# Do manipulations to make the data relevant to our experiment
rho = 1.204E-3 # density of air in g/cm3
# ynew = np.exp(1/(300*rho*y1))

# Length that the particles are transmitted through
L=300
```
# Interpolate for 30 keV
mu = np.interp(30,x1,y1)

# Do a best-fit for theoretical Bremsstrahlung
xdata, ydata = np.loadtxt('bremdata1.txt',usecols=(0,1), unpack=True)
#xdata=xdata*(150.0/1024.0)

xdata2, ydata2 = np.loadtxt('DATA_VU_20160705_195515',usecols=(0,1), unpack=True)

print 'Total number of photons detected for diamond',np.sum(ydata2)

def func(xdata, a, b):
    return (a)/(xdata)+b

# Find the best-fit line of the experiment data
popt, pcov = curve_fit(func, xdata, ydata,p0=[200,2])

a1 = popt[0]
b1 = popt[1]

print "The function is best modeled by:"","a1","/","x","+",b1

xx = np.linspace(5,130,1000)

yy = func(xx, *popt)
#Figure out what the theoretical bremsstrahlung would look like with attenuation

```
yIt = yy*np.exp(-1*L*mu*rho)
```

#Print out what the relative transmitted intensity

```
RTI = np.exp(-1*L*mu*rho)
print 'Relative transmitted intensity',RTI
```

#Find the best-fit line with attenuation

```
popt2, pcov2 = curve_fit(func, xx, yIt,p0=[200,2])
a2 = popt2[0]
b2 = popt2[1]
```

print "The attenuation function is best modeled by:","a2","/","x","+","b2"

# Divide theory equation by attenuation constant to get a new graph.
# Write new files.

```
print 'Absorption Length',1/(mu*rho),'cm'
```

# Find the total number of photons with and without attenuation

```
totalph = np.sum(yy)
totalphwA = np.sum(yIt)
print ',
print 'Total photon counts without attenuation',totalph
print 'Total photon counts with attenuation',totalphwA`
# Calculate the number/rate of counts in detector

# Bunch charge
bc = 20
# electrons/bunch.
Ne = bc/(1.6021E-7)
# Beam energy
Energy = 43
# Relativistic gamma
gamma = Energy/0.511
# Number of photons emitted per bunch. Different for different elements
Nbunch = 10E-3
# Area of the detector (in cm^2)
A = 9E-6
# Distance to detector (in cm)
R = 2.4
# Number of bunches per macropulses
Nb = 100
# Number of macropulses per second
fhz = 1
omegagamma = ((1.5E-3)/3)**2/gamma**2

solidan1 = (A/R**2)/(2*43*10**(-3))
# print solidan1
# print (A/R**2)
# Number of photons emitted into the detector acceptance
print '  
Nphotdet = Ne*Nbunch*(A*(gamma**2)/(4*R**2))
print 'Number of photons emitted into the detector per micropulse:',Nphotdet
# Number of photons in the detector per second
Rphotdet = Nphotdet*Nb*fhz
print 'Number of photons in the detector per second',Rphotdet
print 'Theoretical number of photons detected:',Rphotdet*300
print 'With attenuation, this rate is',Rphotdet*RTI

# Find Nlim. This is the bunch charge that will allow one photon to be detected per
Nlim = (100*4*100*(R**2)*1.6021E-7)/(Nbunch*A*(gamma**2)*Nb*fhz)
Nlim2 = (100*4*100*(R**2)*1.6021E-7)/(Nbunch*A*(gamma**2)*Nb*fhz*RTI)
print 'Nlim is (one photon per bunch)',Nlim,'pC'
print 'With attenuation Nlim is',Nlim2,'pC'
# Plot them

plt.figure()
plt.plot(xdata, ydata, 'ko', label="Original Data")
plt.plot(xx, yy, 'r-', label="(Original) Fitted Curve (y=%s / Energy +%s)"%(a1,b1)
plt.plot(xx, yIt, 'b-', label="Attenuation Curve (y=%s / Energy +%s)"%(a2,b2))
plt.title('Theoretical Bremsstrahlung with Attenuation at 30 MeV')
plt.ylabel('Photon Counts')
plt.xlabel('X-ray Energy (keV)')
plt.legend()
plt.show()
Index

Background, 4
Classical Description of Channeling Radiation, 5
Conclusion, 24
Equations of Motion, 7
Future Work, 23
Multiple Scattering, 9
Quantum Description of Channeling Radiation, 8